Evanescent field sensors based on fibre optic structures

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Abstract

In this work, the behaviour of several transmissive fibre optic based structures when a nanofilm is being deposited will be theoretical and experimentally studied. The technique used to build the nanofilms is the ESA, widely reported in the literature. Two different structures have been selected towards development of practical evanescent field sensors. One is based on hollow core fibres and the other on tapered optical fibres. Some preliminary experimental studies depositing humidity sensitive thin films demonstrating its feasibility will be presented. Up to 4 dB in the optical output power were obtained in both configurations exhibiting similar behaviours. Response time under 2 seconds is also reported and makes them candidates to monitor the human breathing.

Keywords: fibre optic sensor; evanescent field, ionic self-assembly monolayer method, humidity sensors, nanofilms, hollow core fibres, tapered optical fibres.

1 Introduction

There is an increasing interest in developing novel sensing schemes based on several fibre optic structures. Some examples are sensing structures based on holey fibres, omniguide fibres, hollow core fibres, tapered optical fibres, long period gratings, etc [0]. Also, there is a special interest in developing fibre optic based sensors using novel deposition techniques to build sensitive layers in the nanometer scale. Among the different methods for the deposition of thin films one can mention spin coating, thermal evaporation, Langmuir Blodget, ESA (electrostatic self-assembly), and others widely explained in the literature [1-4]. Most of the fibre optic sensors, including the explained here, are based on the modulation of the light intensity produced by the substance to be detected [5], which provokes a change on one of the optical properties of the sensing material (such as absorption or refractive index).

In the present work, two different fibre optic based structures have been analyzed as candidates for novel sensing schemes. They are tapered optical fibres (TOF) and hollow core fibres (HCF). The study of the behaviour of TOF has given rise to numerous investigations either to understand operation mechanisms that regulate the optical power transmission, or to find applications as sensors or devices [6-8]. In the last case, different HCFs have been fabricated composed of, for example, central air hole, a doped silica ring core and a silica cladding or simply a central air hole and a silica cladding with different diameters [9]. This simplest last one has been selected for this work.

Similarly to in TOF, diverse applications using HCF have been reported [9]. Some works have been recently published about their use as waveguides of energetic ultra-short pulses, for trapping and manipulating atoms with guided evanescent fields, for the fabrication of electrically controllable long-period liquid crystal fibre gratings, band-pass filters and even mode converters [10-13]. Also, HCF can be used for the fabrication of optical fibre sensors. As an example, strain sensors based on In-Line Fibre Etalons (ILFE) have been made using a segment of HCF spliced between two sections of multi-mode fibre [14]. In the cited works light is confined in the air core of the HCF.

In both structures, the nano-film has been deposited using the ESA technique, which allows to control the coating thickness in the order of few nanometers [5]. Basically it will be studied the influence of such a humidity sensitive nano-film deposited onto the surface of HCF and TOF based structures towards its applications to humidity measurement.

The remainder of this work is organized as follows. In Section 2, the fabrication and design rules of both structures will be detailed. The explanation of the sensing mechanism is analyzed in section 3. Then the experimental set-up is depicted in section 4. In section 5 some experimental results will be commented. Finally, concluding remarks are given in Section 6.

2 Design and fabrication

2.1 TOF based structure

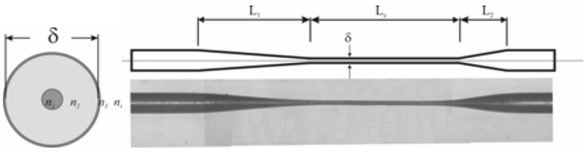

Figure 1. Profile and photograph of a TOF based structure.

In order to fabricate a TOF based structure an optical fibre is narrowed by heating the fibre and applying tension to one end of the fibre while the other end is fixed. Other authors have used a travelling flame or heating a 1-cm-wide platinum furnace as the heat source. With these two methods waist lengths of 50 mm and 10 mm were obtained respectively [15]. In this work an Ericsson FSU-905 splicing unit was used; the fusion splicer is programmed selecting fusion currents lower than those used in fibre splicing and changing the fusion time to a longer value. In this case the fibre was malleable but not degraded by heat, and there was enough time to pull the fibre. With the proposed method, utilizing a standard 1.3 μm single-mode optical fibre (core and cladding diameters of 9.4 and 125 μm respectively), it is possible to get a waist length of 1 mm yielding to a smaller region susceptible to be bent, obtaining a smaller sensor at a lower cost.

In Fig. 1, a photograph of a typical taper profile is shown. The transition zones have normally different lengths because of the technique used for tapering. A tapered fibre can be divided into three regions: a contracting tapered region L_1, a central region (waist) L_c, and an expanding tapered region L_2.

In the light guided by an optical fibre it can be distinguished two components, the component inside the core, and the evanescent component propagating through the cladding. However, as the cladding is much thicker than the core, the interaction of the exponentially decaying component with the external medium is insignificant. When the fibre is tapered the evanescent field interacts with the outer medium modulating the optical power transmitted. Furthermore, when a fibre is tapered the core/cladding interface is redefined in such a way that the core in the tapered region acts as a cladding and the new cladding will be the coating when deposited. Any alteration in the coating (thickness, index of refraction, etc.), will provoke a change of the evanescent field of the travelling light, that will intensity modulate the output optical power.

2.2 HCF based structure

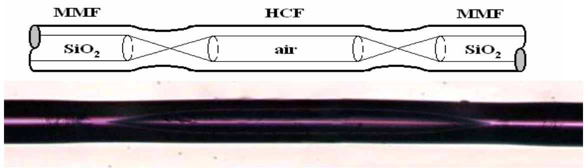

Figure 2. Profile and photograph of a HCF based structure

This structure is schematically shown in Fig. 2 along with a photograph. It consists of one short segment (around 15mm) of hollow core fibre (HCF) spliced between two standard multimode fibres (MMF). Previously, the jacket of the HCF had to be removed. If the HCF and the MMF are spliced together using the appropriate electric arc conditions, the HCF collapses forming a tapered solid fibre in the interface between both fibres (see Fig 2). In these devices, the light that is guided in the core of the lead-in MMF can be coupled to the cladding of the HCF due to the tapered region instead of being confined in the air core. When the light reaches the lead-out MMF, it will be coupled into the silica core again. Because the light is guided by the silica cladding in the HCF region, these devices can be used as evanescent field fibre sensors as will be demonstrated in next sections.

3 Sensing mechanism

The sensing mechanism in these two humidity sensor approaches relies on the transmitted optical power changes accomplished by the interaction of the evanescent field of the light with the humidity sensing coating deposited on the surface of the structure. That is, some water molecules can be trapped at the surface of the sensing coating, altering its optical properties. So, in this case it is clear that, for a given relative humidity constant, the choice of either a hydrophilic or hydrophobic sensing material will determine the size of the water drops trapped on the surface due to the respective affinity or repulsion of the water to the sensing material.

The ESA method is a novel technique already proved for the fabrication of magnetic, electrically conductive, nonlinear optical and other thin film materials on substrates of various sizes, shapes and materials [5]. This method is based on the electrostatic attraction between oppositely charged molecular segments in each deposited monolayer. The ESA process involves several steps. First, a substrate (in this case the optical fibre) is cleaned and chemically treated to produce a charged surface. Then, the substrate is alternately dipped into solutions of cationic and anionic polymers (or appropriately charged inorganic clusters) to create a multilayer thin film.

To make the humidity sensor elements, a solution of Poly R-478 (anthrapyridone chromophore) was used as the anionic electrolyte and exhibits a hydrophilic nature, and poly(diallyldimethyl ammonium chloride)

(PDDA) as the cationic electrolyte with a hydrophobic nature. Using the ESA process, a multilayer structure of the form $[PDDA^{+}/PolyR478^{-}]_n$, where n indicates the total number of bilayers, was built up at the surface of either TOF or HCF based structures. This multilayer behaves as a homogenous optical medium, because each monolayer thickness is on the nanometer scale, so local variations in index occur over lengths quite smaller than an optical wavelength. Furthermore, due to the deposition of alternatively hydrophobic and hydrophilic materials on the surface as the humidity sensing coating, the water molecules are adsorbed at the surface and not absorbed inside the multilayer coating.

4 Experimental set-up

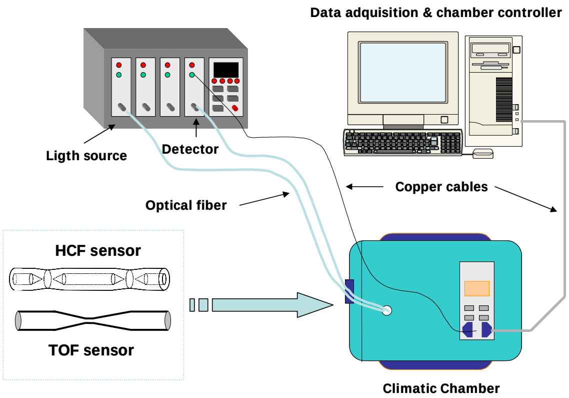

Figure 3. Experimental set-up to characterize the humidity sensors proposed

In order to study the behaviour of the sensors in a variable humidity environment, they were introduced in a climatic chamber, model Challenge 250, from Angelantoni Industrie, Cimacolle, Italy. The climatic chamber is equipped with a humidification-dehumidification system and a cooling-heating system able to change humidity and temperature respectively inside the chamber in a controlled way by means of a PC and configurable software (Winkratos). To complete the set-up, the ends of the structures under study were kept outside the climatic chamber. One of them was connected to a light source module and the other to a power meter module of the same equipment. All the electronic and optical signals were saved simultaneously using the controlling software. This set-up is depicted in Figure 3.

5 Some experimental results

5.1 Coating thickness influence

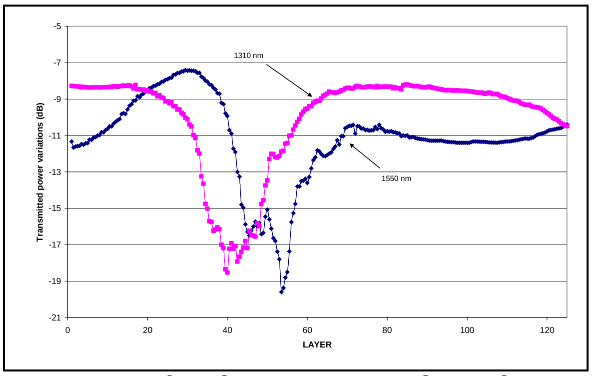

Figure 4. TOF based sensor transmitted optical power as a function of the thickness coating at two different wavelengths 1310 nm and 1550 nm

In Fig. 4 typical TOF constructions curves with the humidity sensitive polymer combination used at two different wavelengths are shown. This humidity sensitive coating has a refractive index higher than the cladding index. In both cases, as the thickness gets increased, the transmitted power decreases until it reaches a minimum that at λ=1310 nm is 10 dB and at λ=1550 nm is 12 dB. Once the minimum peak has been reached the power rise up to a point where all the original power is recovered. For this experiment 125 bi-layers with an approximate thickness of 12 nm each one were needed. The power oscillation shown by these structures depends on the fabrication parameters (taper length, slope waist diameter, etc.), wavelength used, refractive index of the coating deposited, etc. Probably it is important to remark that there is a different mode coupling at different wavelengths giving the possibility to get different humidity behaviors using the same sensor head but replacing the optical source.

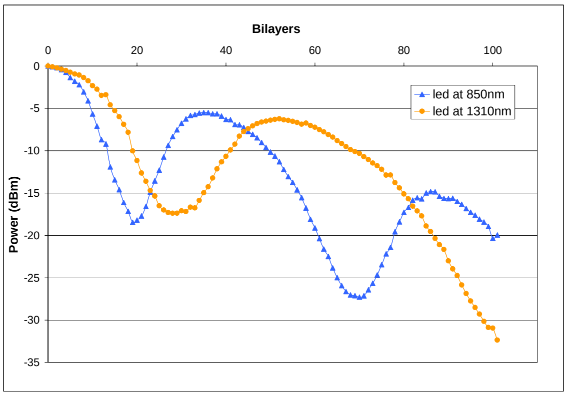

Figure 5. HCF based sensor transmitted optical power as a function of the thickness coating at two different wavelengths 1310 nm and 1550 nm.

Similarly to the previous case, figure 5 shows how the power transmitted by HCF structures goes down in an oscillatory way as the number of nano-layers deposited is increased. The power transmitted follows an oscillatory way whose period and depth, depends on the wavelength used and the geometrical characteristics of the HCF utilized, respectively, as also commented above for the TOF based structure.

5.2 Humidity sensor response

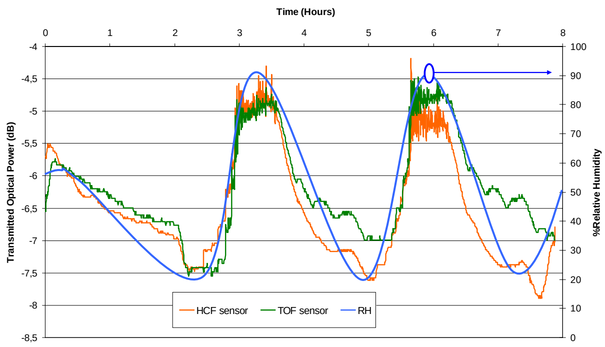

Figure 6. Humidity response comparison between a HCF and a TOF humidity based sensor at a wavelength of 1310 nm.

The ability of the proposed structures to detect humidity was demonstrated using the experimental setup shown in Fig. 3 and explained in section 4. One TOF and one HCF based structures were introduced into the climatic chamber in which the humidity followed the control signal applied from the computer (blue line in figure 6), keeping the temperature at a constant ambient value. The experimental curves obtained are shown in figure 6. Both sensors follow the humidity applied into the chamber with an apparently noisy signal, probably due to the own climate chamber working. Also, the response of the two sensors seems to be repetitive.

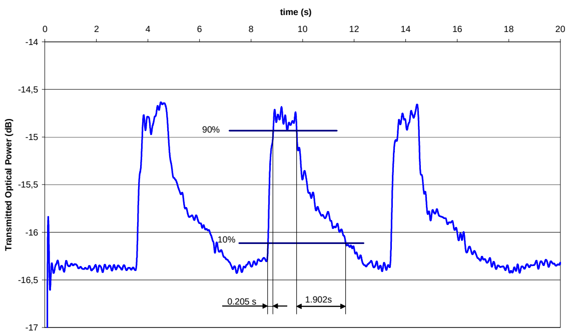

Figure 7. Response of the TOF sensor to human breathing.

To evaluate the response time of these sensors, it was necessary to get the sensor heads exposed to quick changes of the RH. Taking into account that human expiration contains more water vapour than the normal room environment; the sensor head was set 3 cm from a subject's nose. The periodic RH results obtained are shown in Fig. 9. The observed rise and fall response times of the sensor was shorter than 0.3 and 2 seconds, respectively.

6 Conclusions

Two optical fiber based structures (TOF and HCF) have been evaluated towards development of practical humidity evanescent field sensors. By depositing humidity sensitive coatings on the surface of both structures, it has been demonstrated that the ambient humidity can modulate the output optical power transmitted. The deposition technique was ESA. The materials used, Poly R-478 and PDDA exhibited a fast response, with good sensitivity and reproducibility, to changes in the relative humidity of environment. Due to these properties, its application to a breathing-condition monitor became possible, as was experimentally demonstrated.

7 Acknoledgements

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